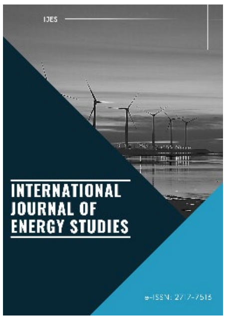
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article

Int J Energy Studies 2025; 10(1): 1203-1225

DOI: 10.58559/ijes.1643588

Received : 20 Feb 2025
Revised : 07 Mar 2025
Accepted : 10 Mar 2025

Novel Hybrid MPPT based on modified incremental conductance-grey wolf optimization for grid connected PV systems

Ahmad M. Nezam[a*], Yunus Yalman[b]

[a]Ankara Yıldırım Beyazıt University, Energy System Engineering, ORCID: 0009-0002-6946-0606
[b]Ankara Yıldırım Beyazıt University, Electrical and Electronics Engineering, ORCID: 0000-0003-1032-9814
*(*Corresponding Author: ahmad.nezam6@gmail.com)*

Highlights

- Design of grid connected PV system is explained.
- Bus voltage controller is discussed to enhance the power quality by making it stabile.
- Decrement of THD methods are shown and MPPT method is evaluated.

You can cite this article as: Nezam AM, Yalman Y. Novel Hybrid MPPT based on modified incremental conductance-grey wolf optimization for grid connected PV systems. Int J Energy Studies 2025; 10(1): 1203-1225.

ABSTRACT

In recent years, the utilization of renewable energy sources has expanded significantly to mitigate the adverse effects associated with conventional energy sources, particularly carbon dioxide (CO_2) emissions. Due to the intermittent nature of the Photovoltaic (PV) system, the output power of the PV system fluctuates which affects the output power and power quality of the power system. Maximum power point tracking techniques (MPPT) are utilized to overcome efficiency and power quality problems. In this paper, a hybrid MPPT algorithm is proposed to improve efficiency and power quality for grid-connected PV systems. The proposed MPPT combines modified incremental conductance and grey wolf Optimization. Incremental Conductance (INC), Modified Incremental Conductance (M_INC), Perturb & Observe (P&O), Modified Perturb & Observe (M_P&O), and Grey Wolf Optimization (GWO) MPPT methods are implemented in MATLAB and compared with the proposed algorithm. The simulation results ensure the outperform of the proposed algorithm to the other algorithms by possessing the lowest THD of 2.31% and it reaches the efficiency of 99.71% with less oscillation at the output.

Keywords: THD, Grid connected PV system, Hybrid modified incremental conductance-grey wolf optimization, MPPT, Power efficiency

1. INTRODUCTION

In recent years, global efforts have increasingly focused on the development and integration of emerging technologies. Solar and wind energies are most interested technologies, to address environmental challenges associated with conventional energy sources, which are major contributors to greenhouse gas emissions.[1], [2]. On-Grid and Off-Grid photovoltaic (PV) systems have significantly increased due to its effectiveness, scalability, versatility, and ease of installation [3], [4]. However, the low conversion efficiency of PV panels, primarily due to the materials used, such as crystalline silicon, necessitates ongoing research and development efforts to enhance efficiency, making it a critical area of study in the scientific community.[5], [6]. Unexpected variations in atmospheric conditions, known as partial shading conditions (PSC), can further reduce efficiency and increase the total harmonic distortion (THD), thereby deteriorating power quality in grid-connected PV systems. Additionally, the inverters used in grid-connected PV systems significantly influence THD, impacting overall system performance [7].

Maximum power point tracker (MPPT) algorithms can be the solution to overcome the THD and overall efficiency. The MPPT controls the duty cycle of the DC-DC converter by tracking the maximum power point (MPP) produced by the panels [8].

MPPT techniques are generally categorized into conventional and unconventional methods. Conventional methods such as Incremental Conductance [9], Perturb & Observe [10], Fractional Short Circuit Current [11], and Fractional Open Circuit Voltage [12] In the other side, unconventional approaches including Particle Swarm Optimization [13], Fuzzy Logic [14], Artificial Neural Network [15], Artificial Bee Colony [16], and Cuckoo Search [17]. However, the traditional algorithms sometimes fails to track global maximum power point (GMPP). For this reason, hybrid MPPT algorithms are proposed to solve this issue such as Perturb & Observe-Particle Swarm Optimization [18], Incremental Conductance-Dragonfly Optimization [19], and Artificial Neural Network-Variable Step Perturb & Observe-Fuzzy Logic Controller [20].

Table 1 illustrates some methods to reduce the THD in grid connected PV systems including different types of MPPT algorithms with and without filters. Outcomes of the papers show that proper MPPT algorithms have obvious effect to reduce the THD and enhance the overall efficiency.

In this study a new MPPT algorithm is developed to enhance the power quality of the grid connected system. The proposed hybrid M_INC-GWO MPPT algorithm's performances are compared with INC, P&O, M_INC, M_P&O, and GWO algorithms. MPPT algorithms have been simulated under MATLAB/SIMULINK to evaluate the effect of MPPT algorithms on the THD and efficiency for grid-connected PV system. The following sections are prepared as: Section 2 is the theoretical background including PV panel, boost converter, MPPTs, inverter, and inductive filter. Section 3 covers the analytic results of the simulations including key factors such as THD at the MPP, tracking efficiency, power oscillation, grid current, and bus voltage stability. In section 4 conclusion is given.

Table 1. Literature review

Ref	Method	Comments
[21]	Passive LCL filter	Using an LCL filter improved the power quality where the THD is under the standard limitation
[22]	Passive LC filter	Implementing an LC passive filter has significant improvement in reducing the THD from 91% to 2.62%.
[23]	Passive L and LCL filters	The THD under the L filter was good around 1.56% while the LCL filter has remarkable enhancement where the THD is 0.07%
[24]	three-level neutral point clamped Shunt active power filter	Under varying conditions, the THD is still less than the standard.
[25]	Shunt active power filter controlled by Bat and Golden Eagle algorithms	The simulations show that controlling the Shunt active filter by proper algorithms will enhance the THD, where Golden Eagle controlled has 3.17% and Bat controlled 1.91% of THD.
[26]	Series active filter	The filter was designed on the DC side of the grid-connected PV system, where an inductor, two capacitors, and four transistor-diode pairs were installed in series to reduce the THD. As result, the THD reduced to 2.8% and 9.58% for voltage and current respectively.
[27]	MPPT algorithms	Different MPPT algorithms such as perturb and observation, incremental conductance, fuzzy logic control, and Sliding mode control can affect the THD. In this paper, the THDs are 3.68%, 3.48, 1.99%, and 1.34% respectively.
[28]	MPPT algorithms	Three algorithms were compared to figure out the effect of MPPT algorithms to reduce the THD which are P&O, optimized P&O, and gravitational search. The proposed optimized P&O has the lowest THD of 3.11%.
[29]	Hybrid shunt active filter	The atomic orbital search-feedback artificial tree technique has a significant decrease in THD which is 1.1% according to

		other techniques such as enhanced particle swarm optimization, fuzzy logic control, and sliding mode control.
[30]	LCL filter-based Modified INC	The effect of the modified INC has reduced the THD of the system from 1.18% to 1.15% under the LCL passive filter.
[31]	Hybrid MPPT algorithm	The hybrid Bat-P&O algorithm has low THD (0.32%) compared to Bat (2.29%) and P&O (6.12%) algorithms separately
[32]	FLC-MPPT	Fuzzy Logic Controller has significantly reduced the THD from 3.51% to 0.91% comparing to P&O algorithm.
[33]	LCL filter based ANN algorithm	The LCL filter has enhanced the THD by reducing 99.78% comparing to without filter. Where the THD is dropped from12% to less than 0.1%.
[34]	Shunt active power filter based on hybrid FPSO	By tracking the MPP using hybrid fuzzy particle swarm optimization and controlling the active filter with FLC, the THD has reduced to 2.22% comparing to the traditional algorithms.

2. THEORETICAL BACKGROUND

The produced power from the PV can vary depending on the irradiance and temperature. To clarify, the change in the inputs will affect maximum power point of the PV. In this paper, the temperature is constant while the irradiance varies as illustrated in Figure 1.

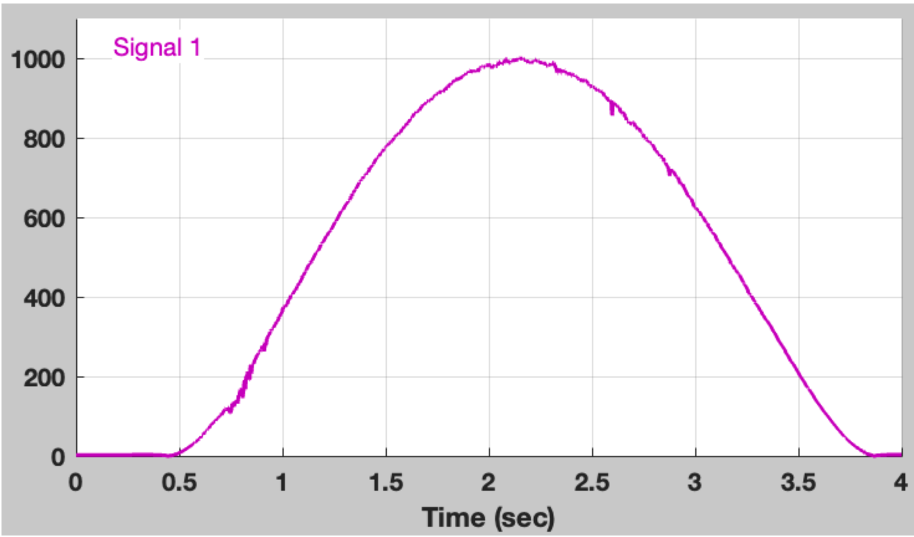


Figure 1. Input irradiance

The design of the grid-connected PV systems is shown in Figure 2, where the system has five main parts which are PV, boost converter, DC-AC inverter, inductive filter, and grid.

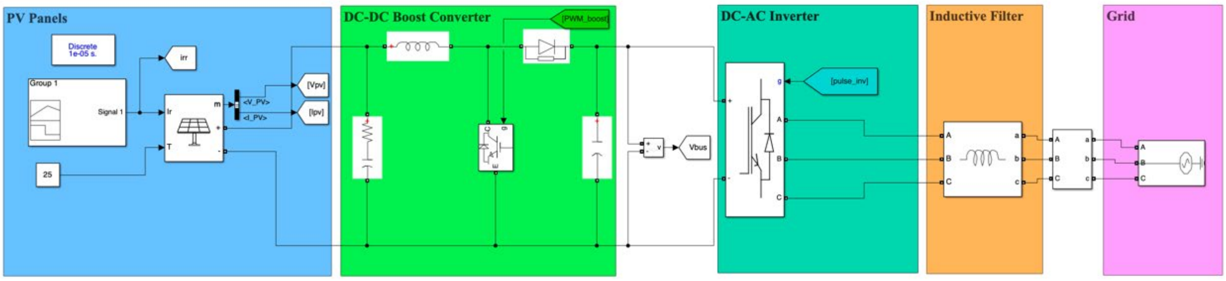


Figure 2. Grid-connected PV system

2.1. PV Panel

PV panels consist of cells composed of semiconductor materials which are convert the solar radiation to electrical energy. These cells generate an electric current when sunlight touches them because photons absorb energy and transfer electrons within the cell. In addition, these cells can be modeled by considering an equivalent circuit of PV panel. Generally, the equivalent circuit has one or more diodes which are paralyzed to the current source harvested from the cells. The equivalent circuit for one diode is presented in Figure 3, where the output current can be evaluated by using Kirchhoff's Current Law [35].

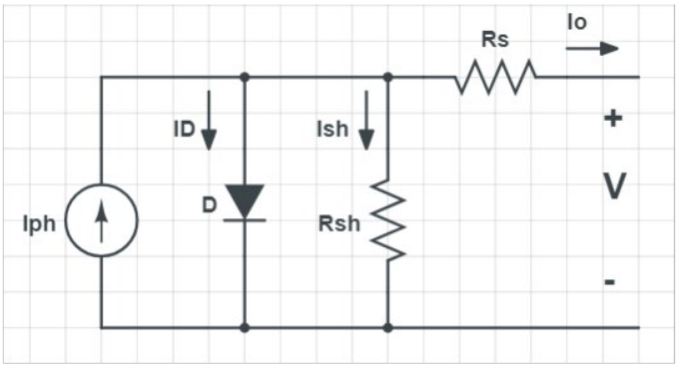


Figure 3. Equilibrium circuit of single diode PV cell

$$I_o = I_{ph} - I_{SD}\left[\exp\left(\frac{q(V_{PV}+I_oR_S)}{nkT}\right)-1\right] - \frac{V_{PV}+I_oR_S}{R_{sh}} \quad (1)$$

Where I_o, I_{ph}, I_D, I_{sh}, I_{SD}, q, V_{PV}, n, k, T, R_S, and R_{Sh} are output current, photocurrent, diode current, shunt current, Reverse saturation current, electron charge $= 1.6 \times 10^{-19}\ C$, PV voltage, Ideality factor, Boltzmann's constant $= 1.38 \times 10^{-23}\ {}^{J}/_{K}$, Temperature, Series resistance, and Shunt resistance respectively.

2.2. Boost Converter

The working principle of a boost converter is to step up the voltage to the required output voltage for grid-connected PV systems. The general circuit of the boost converter is shown in Figure 4, [36]. To design the boost converter in proper way, the used parameters must be evaluated correctly. The calculations can be done using equations 5, 6, 7, and 8.

$$D = 1 - \frac{V_{PV}}{V_0} \tag{5}$$

$$L = \frac{V_{PV} \times D}{f_s \times \Delta I_L} \tag{6}$$

$$C_0 = \frac{I_0 \times D}{f_s \times \Delta V_0} \tag{7}$$

$$R = \frac{{V_0}^2}{P} \tag{8}$$

Where D, V_{PV}, V_0, L, f_s, ΔI_L, C, I_0, ΔV_0, and P are duty cycle, input voltage, output voltage, inductor, switching frequincy, input ripple current, capacitor, output current, output ripple voltage, and operating power respectively [37].

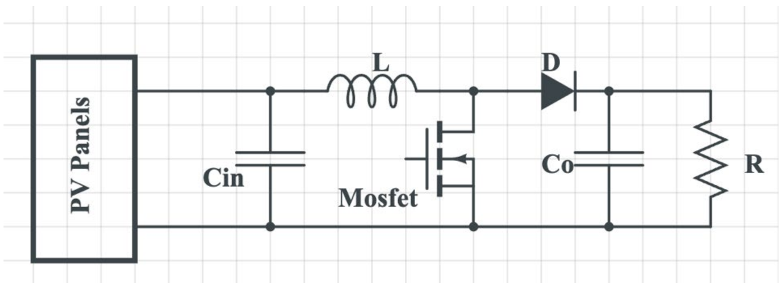


Figure 4. Boost converter

2.3. MPPT Algorithms

MPPT algorithms play a significant role in harvesting the maximum possible energy from the PV panels by adjusting the duty cycle of the used switch in the boost converter [38]. Selecting MPPT algorithms requires some critical points to be considered such as efficiency, settling time, robustness, oscillation and some other points.

2.3.1. INC

INC algorithm is one of the most used MPPT algorithms due to its ease implementation and fast tracking feature by using current deviations comparison $\frac{dI}{dV}$. As illustrated in Figure 5, the INC starts by reading the measured voltage and current from the PV panel. Then the difference in voltage (dV) and current (dI) from the previous iteration will be calculated to adjust the duty cycle (D) value which increased or decreased by small value (ΔD). The ΔD is a constant value less than 0.001. To evaluate the instantaneous power which decides the position of the measuring point Equation 9 is implemented.

$$P = IV \Rrightarrow \frac{dP}{dV} = I + V\frac{dI}{dV} \tag{9}$$

From the Equation 9, when the slop is equal to zero means that the point is at the maximum, so the duty cycle remains same to extract the MPP if not the duty cycle will increase or decrease depending on the position of the slop [39].

2.3.2. M_INC

The M_INC enhances the overall efficiency of the system and reaches the MPP faster than traditional INC. As seen in Figure 6, the algorithm will keep the duty cycle same as previous if the measuring point near to the MPP. Unchanged duty cycle is done by implementing the absolute value of the difference in power dP (n) $n < 0.005$ to reduce the oscillation at the steady state which increases the system's efficiency. From the other side, when the duty cycle is required to be increased or decreased the small change (ΔD) will be multiplied by absolute value of dP (n) which leads to reach the MPP faster than conventional INC algorithm.

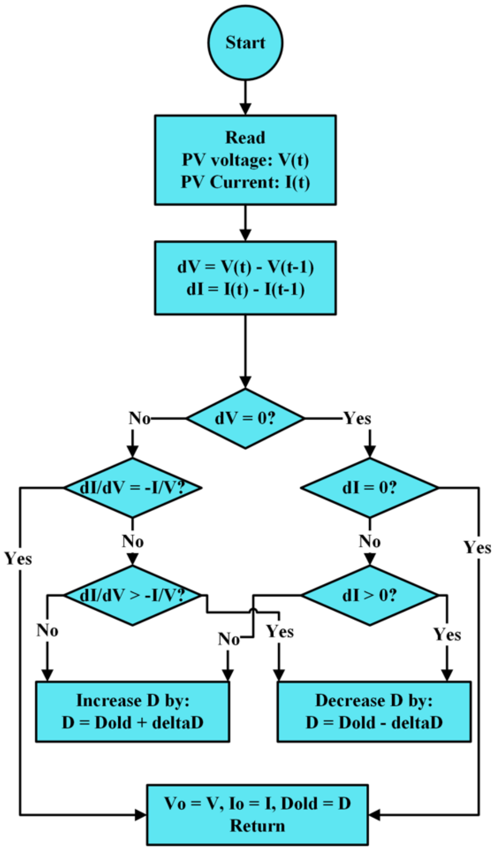


Figure 6. INC algorithm

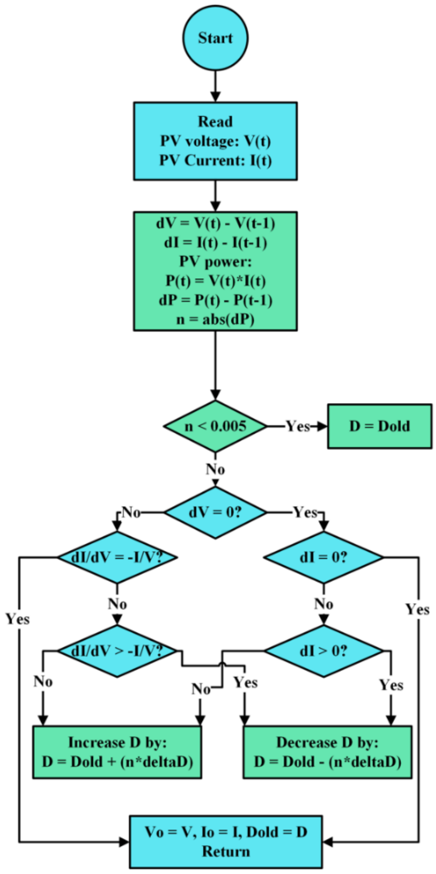


Figure 5. M_INC algorithm

2.3.3. P&O

P&O algorithm is one of highly used conventional algorithm similar to INC. The main difference between the P&O and INC is that the P&O deals with the power directly as illustrated in Figure 7 [40]. The algorithm starts by measuring the voltage and current from the PV panel and then computes the power by multiplying the voltage and current. After evaluating the power extracted from the PV panel, the algorithm calculates the differences in voltage and power from its one previous iteration (dV and dP). After calculation, the P&O algorithm compares the values starting with the dP if it equals zero or not to figure out if the point at the MPP or not. Lastly, by comparing the dV with zero the duty cycle is increased or decreased depending on the position of the MPP.

2.3.4. M_P&O

Similar modification of M_INC is implemented to P&O algorithm to improve performance of P&O . As seen in Figure 8, the value of duty cycle is limited when the point is near to the MPP by comparing the value with absolute $dP, n < 0.005$. In addition, the increment and decrement of the duty cycle when the $dP \sim = 0$ will be faster due to the multiplication of the small delta (ΔD) to n.

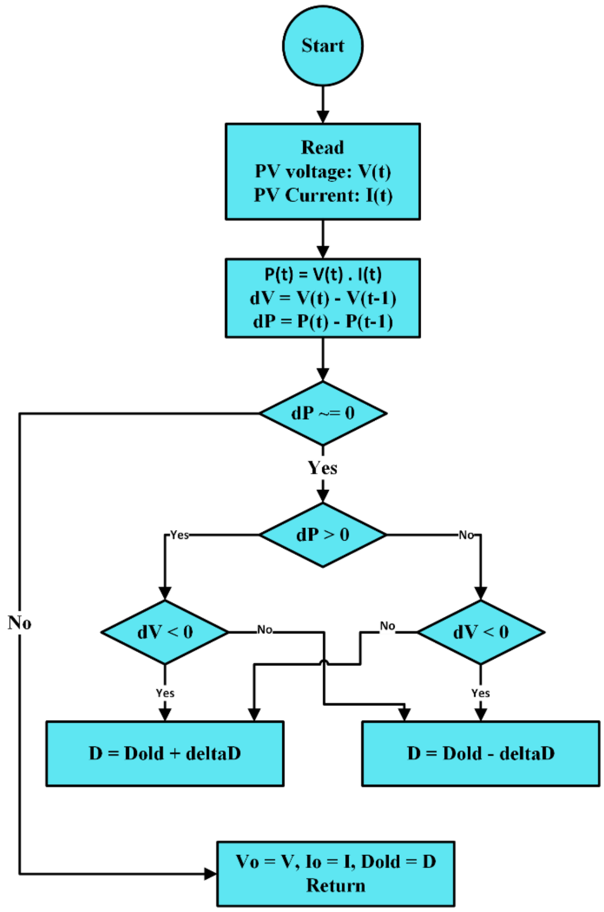


Figure 7. P&O algorithm

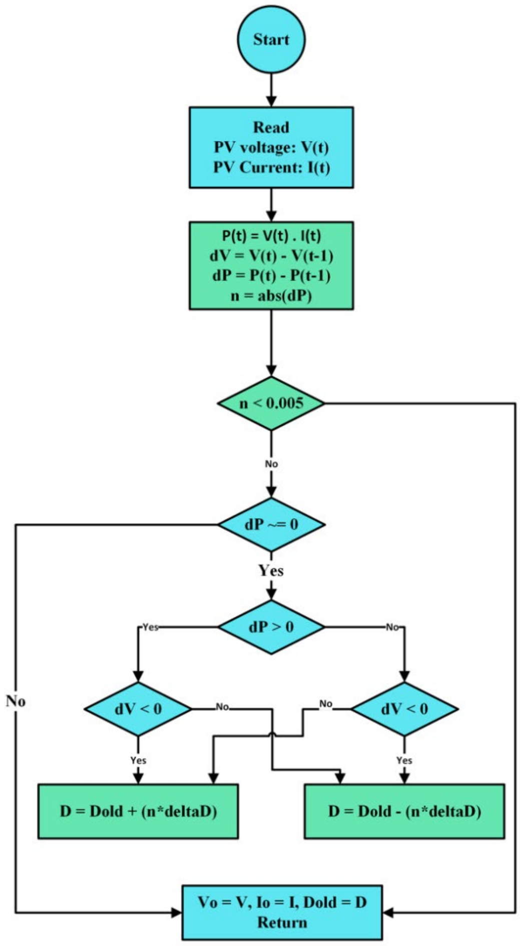


Figure 8. MP&O algorithm

2.3.5. GWO

GWO is unconventional algorithm that inspired from the real behavior of the wolfs, where the used technique for hunting the prey will go through some processes such as when to hunt, attack, take rest, change the prey, change the position etc. These processes will be leaded by alpha which is the fitness value for tracking the MPP in PV system. Generally, the wolfs will be divided into four groups at the head of hierarchy alpha takes a place, where the others will inform the leader with the last updates. Following the leader, Beta will be in the second place which helps the alpha directly. For the last two places, delta and omega take place to get the available solutions to the herd so the leader will decide which process will be implemented.

The same concept is realized to evaluate the MPP, where the number of members at the herd will search for different positions and values of the power coming from the PV system. Then, by informing the fitness and updating the fitness' value, the positions will be updated for each wolf.

After convergence satisfied, the MPP will be found by using GWO algorithm otherwise the herd will go to next iteration. The flowchart of implementing GWO is shown in Figure 9, where the number of wolfs (i) is selected and the voltage and current are measured at the starting point. Before evaluating the best result, the fitness will be calculated and after finding the best result the satisfaction of convergence will be in process to decide if the system goes to next iteration [41].

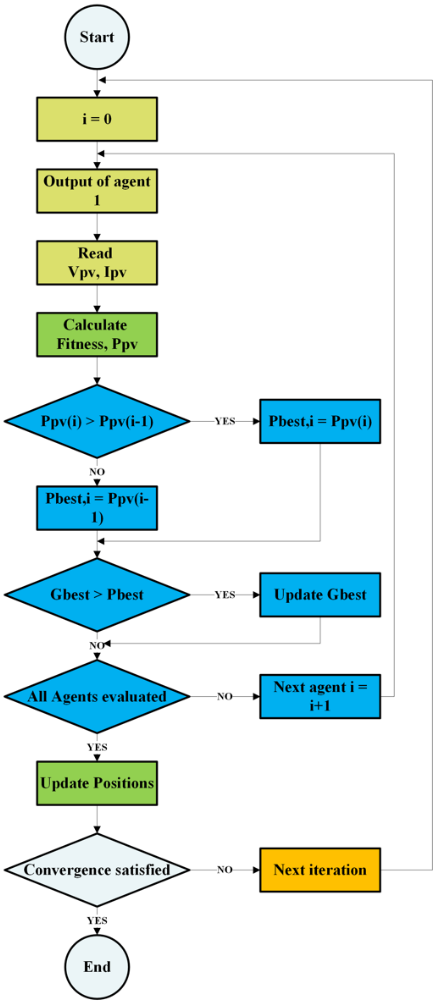


Figure 9. GWO algorithm

2.3.6. Hybrid M_INC-GWO

M_INC-GWO algorithm combines the advantages of the M_INC and GWO to have the best possible output for all the necessary parameters such as THD, efficiency, stability. The flowchart as illustrated in Figure 10; after measuring the input voltage and current from the PV system the algorithm starts with the GWO until the best result is found due to the variation of the irradiance then the M_INC algorithm will proceed by evaluating more accurate value. Otherwise, the hybrid algorithm will act as M_INC only.

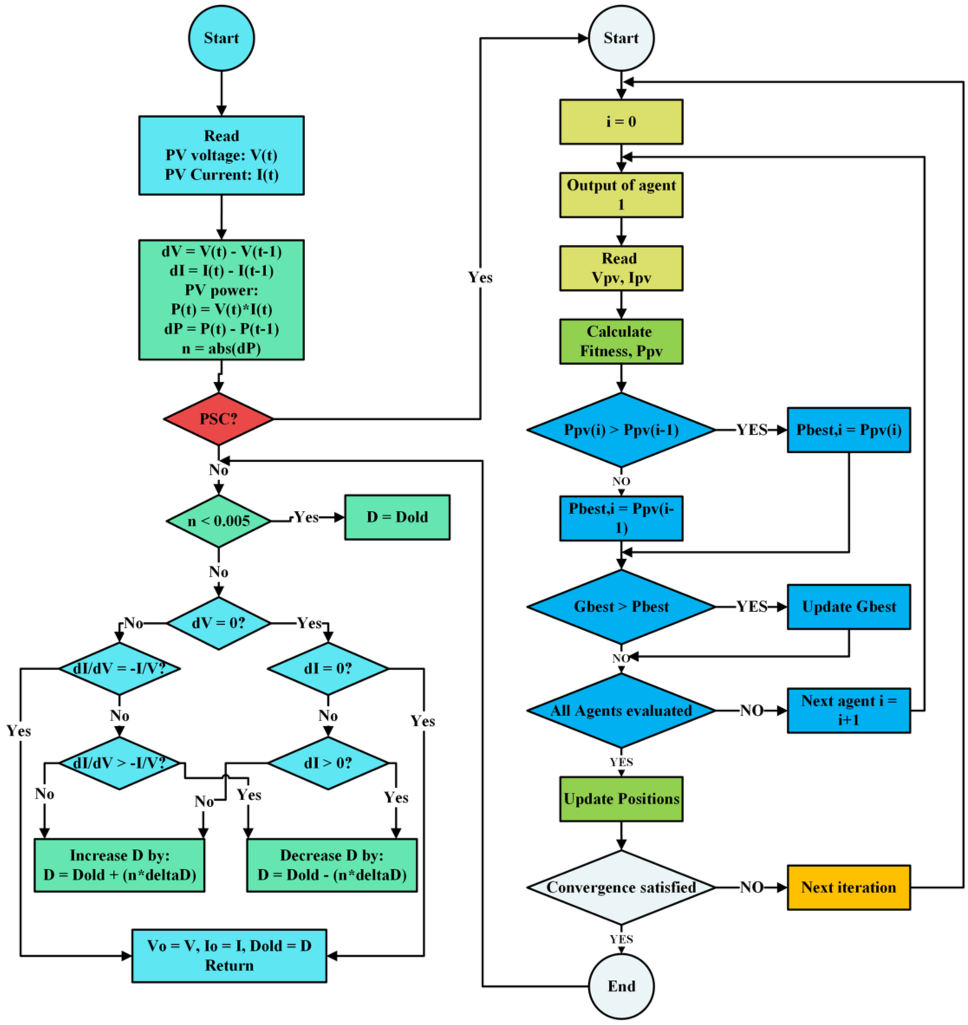


Figure 10. Hybrid M_INC-GWO algorithm

2.4. Inverter

The usage of inverter is to change the waveform of the harvested DC voltage from the PV panel to AC voltage considering the magnitude and frequency. General overview of inverter control is shown in Figure 11. PI controllers, park transformation and PLL are applied in control structure.

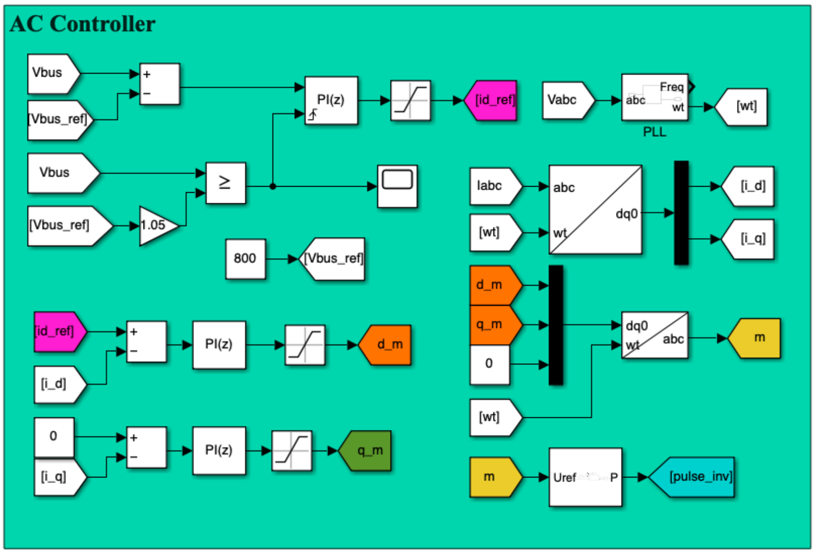


Figure 11. Inverter controller parameters

2.5. Inductive Filter

Inductance filter (L_f) is used to limit the harmonic issue of grid connected PV system, where the value of L_f can be calculated as shown in Equation 10.

$$L_f = \frac{0.1*Vinv}{2*Pi*f*(P_{pv}/3)} \tag{10}$$

Where $Vinv, f,\ and\ P_{pv}$ are phase to phase inverter voltage, frequency of the grid, and total system power which is PV power. The P_{pv} is divided by three to measure the inductance value for each phase [42]. For all cases the inductive filter is 2.8mH.

3. ANALYTIC RESULTS

This study presents a simulation of a grid-connected PV system using MATLAB/Simulink, as illustrated in Figure 12. The parameters of the PV panel, boost converter, and grid are detailed in Tables 2, 3, and 4 respectively. The INC, M_INC, P&O, M_P&O, GWO, and the proposed M_INC-GWO algorithms are tested to determine the effects of the MPPT algorithms on THD at the MPP, tracking efficiency, power oscillation, grid current, and bus voltage stability.

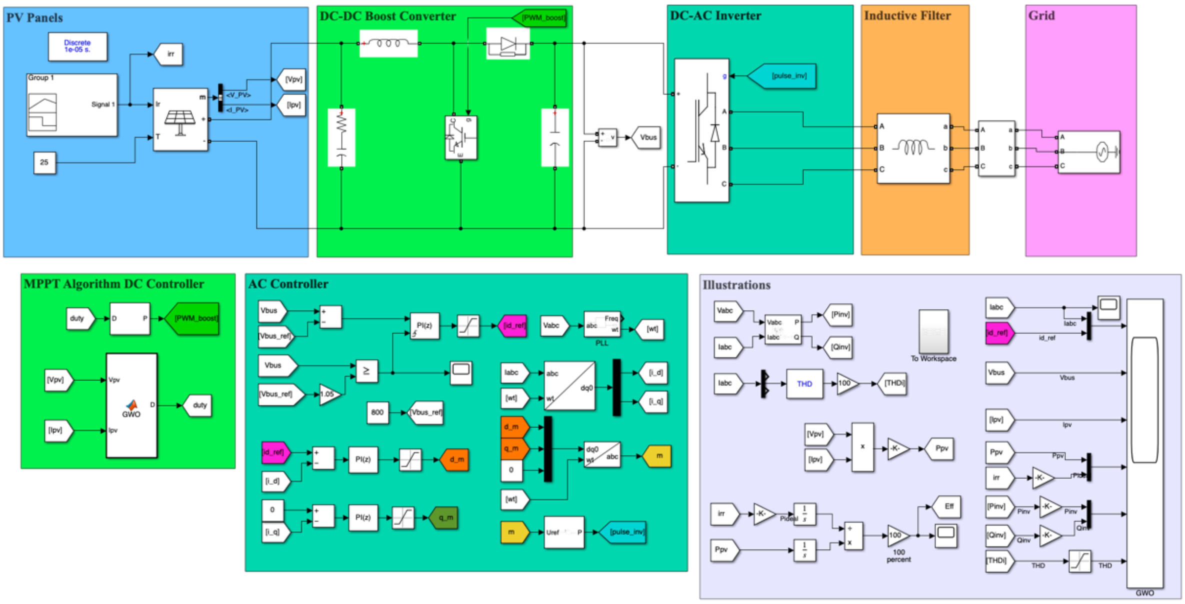


Figure 12. Gird connected PV system Simulink

Table 2. PV parameters

Parameters	Name	Value
V_{OC} (V)	Open-circuit voltage	36.3
I_{SC} (A)	Short-circuit current	7.84
V_{mp} (V)	MPP voltage	29
I_{mp} (A)	MPP current	7.35
P_{MPP}(W)	MPP power	213.15
K_v (V/°C)	Temperature coefficient of the V_{OC}	-0.36099
K_i (A/°C)	Temperature coefficient of the I_{SC}	0.102
N_s	Number of cells per module	60
	Parallel strings	17
	Series-connected modules per string	14

Table 3. Boost parameters

Input C and R	Output Capacitor	Inductor	Switch Frequency
$100\mu F$ and 0.1mΩ	$1000\mu F$	$1.623mH$	$5KHz$

Table 4. Grid parameters

Configuration	Phase-to-phase voltage (Vrms)	Phase angle of phase A (degrees)	Frequency (Hz)
Yg	380	0	50

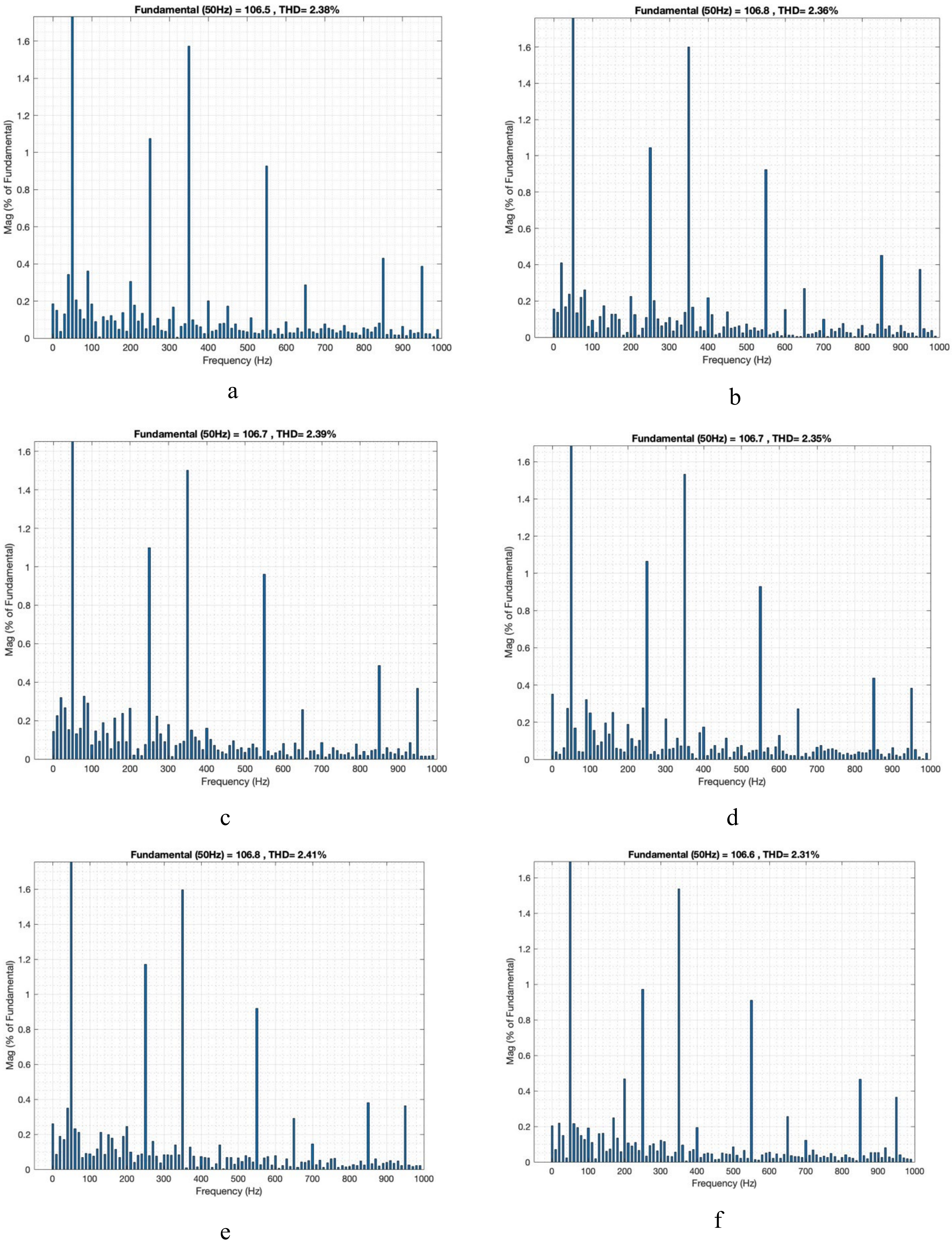


Figure 13. THD values for each MPPT algorithms a) INC, b) M_INC, c)P&O, d) MP&O, e) GWO, f) M_INC-GWO

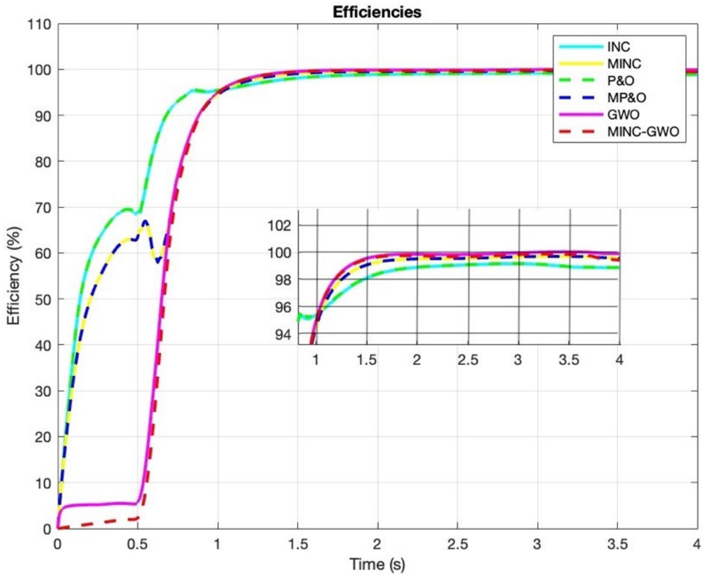


Figure 14. Tracking efficiencies of the MPPT algorithms

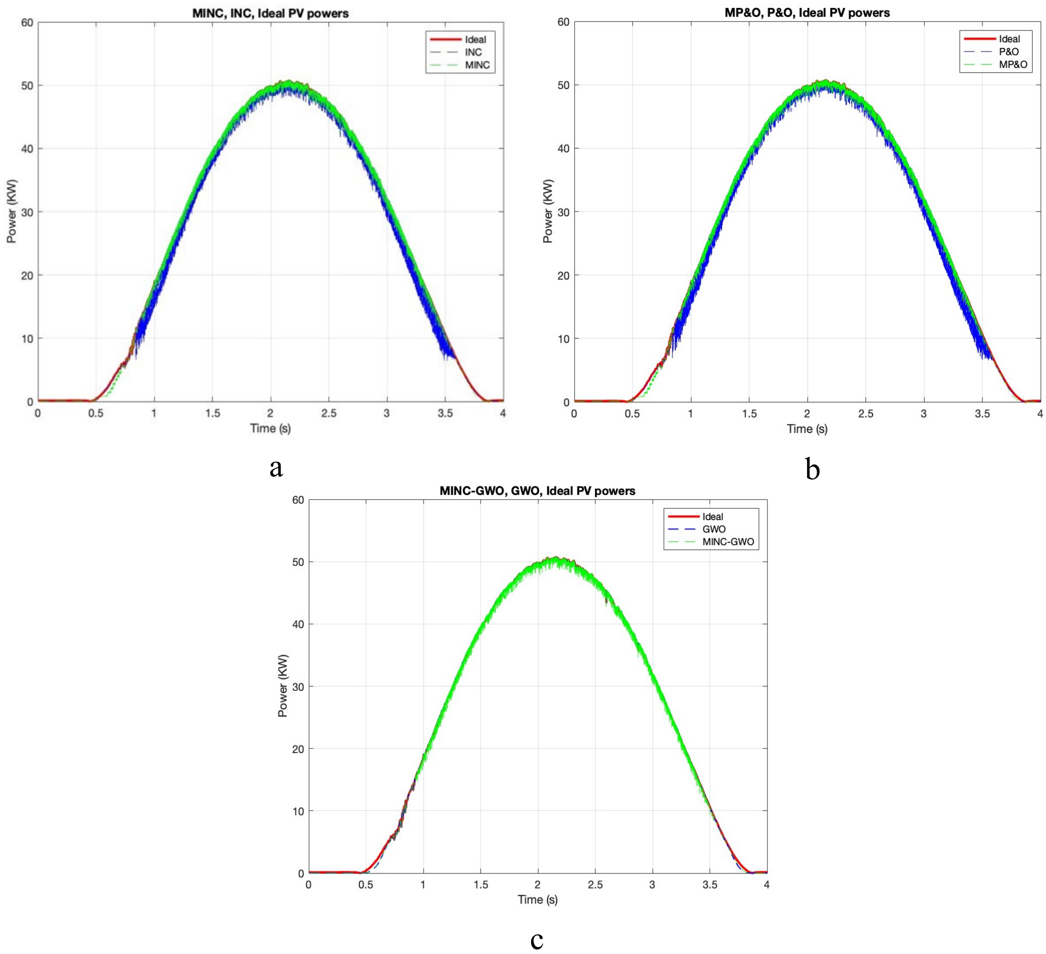


Figure 15. PV power oscillations for each MPPT algorithms a) INC and M_INC, b) P&O and MP&P, c) GWO and M_INC-GWO

Table 5. The results of the MPPT algorithms

MPPT/parameters	THD (%)	Efficiency (%)	Oscillation
INC	2.38	99.05	High
M_INC	2.36	99.64	Low
P&O	2.39	99.05	High
M_P&O	2.35	99.64	Low
GWO	2.41	99.83	Zero
M_INC-GWO	2.31	99.71	Low

The results for MPPT algorithms are demonstrated in Table 5. As shown in Table 5, after modifying INC algorithm the THD is reduced from 2.38% to 2.36%, the efficiency is enhanced from 99.05% to 99.64%, and the power oscillation is low. The THD is improved from 2.39% to 2.35% for P&O algorithm, and the other parameters has same values as INC and M_INC. Although the oscillation and efficiency of GWO algorithm are superior to traditional and modified algorithms, the THD is higher in comparison to them. However, the proposed algorithm has the advantages of GWO and M_INC by enhancing the tracking efficiency, PV power oscillation, and reducing the THD at MPP where the minimum THD of 2.31% is evaluated by M_INC-GWO comparing to the rest, leading to make the proposed algorithm outperform the others in overall. In addition, the other used algorithms have THD under the standard limitation which is 5%[43]. The output simulations of all algorithms for THD, efficiencies, and power oscillations are illustrated in Figure 13, 14, and 15 respectively. From the figures, the modified algorithms reduce both THD and power oscillations according to the conventional MPPT algorithms. From other side, the efficiency of system is increased.

Figure 16 and 17 show grid current and DC bus voltage level for MPPT algorithms, respectively. As seen from Figures, the DC bus voltage and grid current is stable.

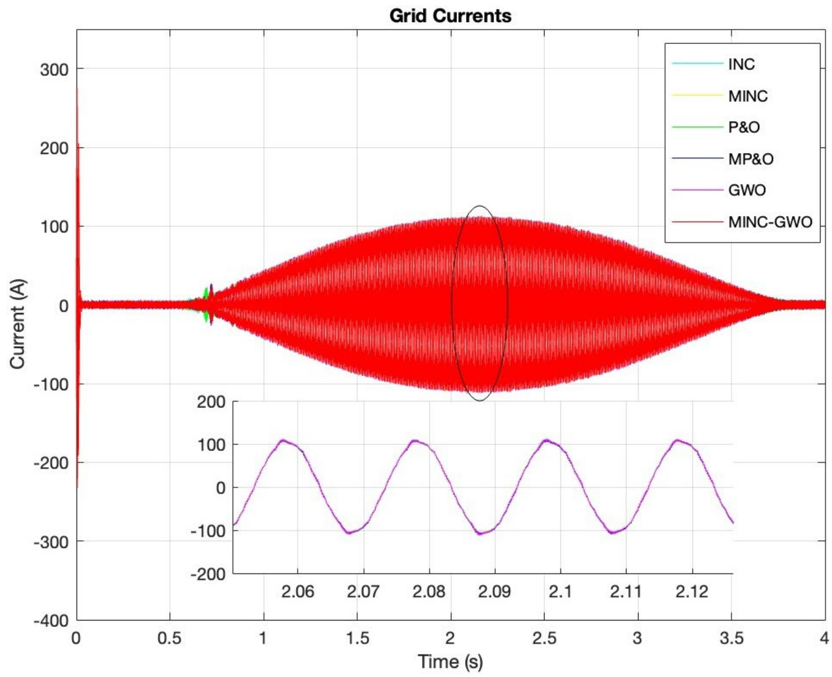


Figure 16. Grid currents for MPPT algorithms

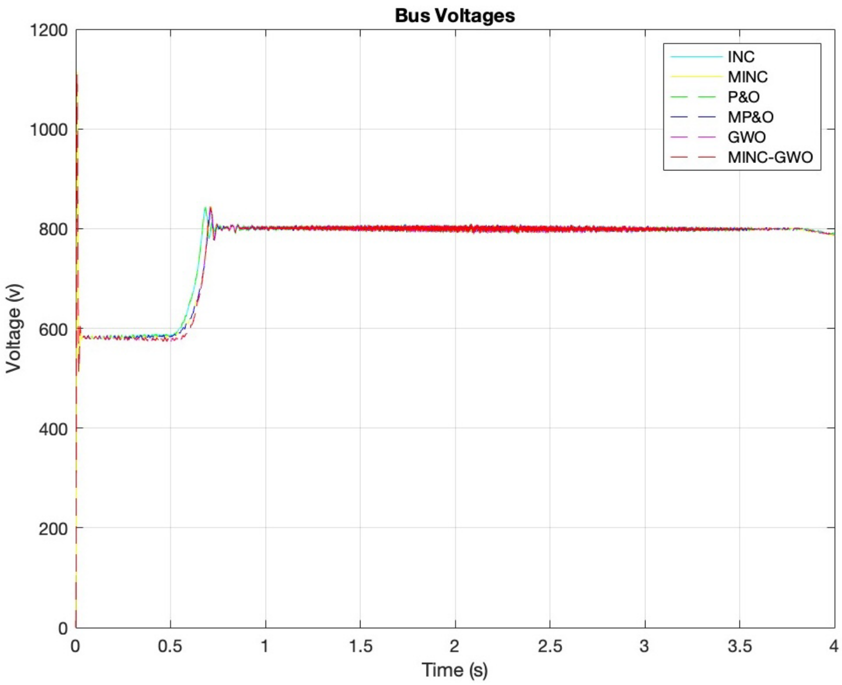


Figure 17. DC bus voltages for MPPT algorithms

4. CONCLUSION

This paper presents the design and simulation of grid connected PV system using the proposed hybrid MPPT algorithm called M_INC-GWO based on combination of a Modified Incremental Conductance and Grey Wolf Optimization. The simulation of M_INC-GWO was under

MATLAB/SIMULINK environment for enhancing the key parameters of the system such as THD at the MPP, tracking efficiency, power oscillation, grid current, and bus voltage stability. Simulation results of M_INC-GWO are compared with INC, M_INC, P&O, MP&O, and GWO. The simulation results show that all MPPT algorithms have notable tracking efficiencies over 99% and the M_INC-GWO has reached to 99.71%. The proposed algorithm demonstrates superior performance in reducing THD, achieving a value of 2.31%. In comparison, the THD values for INC, M_INC, P&O, MP&O, and GWO algorithms are 2.38%, 2.36%, 2.39%, 2.35%, and 2.41%, respectively. As a results, proposed method improve the power quality and efficiency of PV system.

NOMENCLATURE

PV	Photovoltaic
THD	Total Harmonic Distribution
MPPT	Maximum Power Point Tracker
MPP	Maximum Power Point
GMPP	Global Maximum Power Point
INC	Incremental Conductance
M_INC	Modified Incremental Conductance
P&O	Perturb & Observe
M_P&O	Modified Perturb & Observe
GWO	Grey Wolf Optimizer
M_INC-GWO	Modified Incremental Conductance- Grey Wolf Optimizer
DC	Direct Current
AC	Alternative Current
PSC	Partial Shading Condition

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ahmad Mohammad Nezam: Writing, Methodology, Analysis, Simulation.

Yunus Yalman: Writing, Methodology, Review & Editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Abed AM, Nazari MA, Ahmadi MH, Mukhtar A, Kumar R, Gharib N. Power generation by utilization of different renewable energy sources in five Middle Eastern countries: Present status, opportunities and challenges. Sustainable Energy Technologies and Assessments 2025; 73:104101.

[2] Mittelstädt N, Manske D, Thrän D. The development of ground-mounted photovoltaic systems next to transport routes. Renewable and Sustainable Energy Reviews 2025; 208:114978.

[3] Badea AM, Manaila-Maximean D, Fara L, Craciunescu D. Maximizing solar photovoltaic energy efficiency: MPPT techniques investigation based on shading effects. Solar Energy 2025; 285:113082.

[4] Bamisile O, Acen C, Cai D, Huang Q, Staffell I. The environmental factors affecting solar photovoltaic output. Renewable and Sustainable Energy Reviews 2025; 208:115073.

[5] Jing Y, Zhu L, Yin B, Li F. Evaluating the PV system expansion potential of existing integrated energy parks: A case study in North China. Applied Energy 2023; 330:120310.

[6] Gruner VF, Zanotti JW, Santos WM, Pereira TA, Schmitz L, Martins DC, Coelho RF. Modified current sensorless incremental conductance algorithm for photovoltaic systems. Energies 2023; 16(2):790.

[7] Zaghba L, Borni A, Benbitour MK, Fezzani A, Alwabli A, Bajaj M, Dost Mohammadi SA, Ghoneim SS. Enhancing grid-connected photovoltaic system performance with novel hybrid MPPT technique in variable atmospheric conditions. Scientific Reports 2024; 14(1):8205.

[8] Mishra VL, Chauhan YK, Verma KS. A new hybrid swarm intelligence-based maximum power point tracking technique for solar photovoltaic systems under varying irradiations. Expert Systems with Applications 2025; 264:125786.

[9] Yaqoob SJ, Kamel S, Jurado F, Motahhir S, Chalh A, Arnoos H. Efficient and cost-effective maximum power point tracking technique for solar photovoltaic systems with Li-ion battery charging. Integration 2025; 100:102298.

[10] Addawe A, Mahmood MK, Karim SM, Nezam AM. Analysis of Perturb and Observe MPPT Under Varying PV Operating Climatic Conditions. In2024 21st International Multi-Conference on Systems, Signals & Devices (SSD) 2024; 92-97. IEEE.

[11] Fapi CB, Touré ML, Camara MB, Dakyo B. MPPT based Fractional Short-Circuit Current-Model Predictive Control for PV System in Real Weather Conditions for Heat-Pump Applications. In2024 International Conference on Intelligent Systems and Computer Vision (ISCV) 2024; 1-6. IEEE.

[12] Çakmak F, Aydoğmuş Z, Tür MR. Analysis of open circuit voltage MPPT method with analytical analysis with perturb and observe (P&O) MPPT method in PV systems. Electric Power Components and Systems 2024; 52(9):1528-42.

[13] Regaya CB, Hamdi H, Farhani F, Marai A, Zaafouri A, Chaari A. Real-time implementation of a novel MPPT control based on the improved PSO algorithm using an adaptive factor selection strategy for photovoltaic systems. ISA transactions 2024; 146:496-510.

[14] Xia K, Li Y, Zhu B. Improved photovoltaic MPPT algorithm based on ant colony optimization and fuzzy logic under conditions of partial shading. IEEE Access 2024; 12:44817–44825.

[15] Abouzeid AF, Eleraky H, Kalas A, Rizk R, Elsakka MM, Refaat A. Experimental validation of a low-cost maximum power point tracking technique based on artificial neural network for photovoltaic systems. Scientific Reports 2024; 14(1):18280.

[16] Qi P, Xia H, Cai X, Yu M, Jiang N, Dai Y. Novel global MPPT technique based on hybrid cuckoo search and artificial bee colony under partial-shading conditions. Electronics 2024; 13(7):1337.

[17] Mariprasath T, Basha CH, Khan B, Ali A. A novel on high voltage gain boost converter with cuckoo search optimization based MPPTController for solar PV system. Scientific reports 2024; 14(1):8545.

[18] Nunes H, Teixeira F, Pombo J, Mariano S, do Rosário Calado M. A Novel Hybrid MPPT Method Based on Particle Swarm Optimization and P&O Assisted by Spline Interpolation Technique. In2024 IEEE International Conference on Environment and Electrical Engineering and 2024 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) 2024; 1-7. IEEE.

[19] Sarwar S, Javed MY, Jaffery MH, Arshad J, Ur Rehman A, Shafiq M, Choi JG. A novel hybrid MPPT technique to maximize power harvesting from PV system under partial and complex partial shading. Applied Sciences 2022; 12(2):587.

[20] Masry MZ, Mohammed A, Amer F, Mubarak R. New hybrid MPPT technique including artificial intelligence and traditional techniques for extracting the global maximum power from partially shaded PV systems. Sustainability 2023; 15(14):10884.

[21] Abbas HH, Shafiee Q, Bevrani H. Optimal passive LCL filter design for grid-connected converters in weak grids. Electric Power Systems Research 2024; 235:110896.

[22] Adak S. Harmonics mitigation of stand-alone photovoltaic system using LC passive filter. Journal of Electrical Engineering & Technology 2021; 16(5):2389-96.

[23] Cengiz M, Duman T. Design and analysis of L and LCL filters for grid-connected HNPC inverters used in renewable energy systems. Balkan Journal of Electrical and Computer Engineering 2024; 12(1):53-61.

[24] Amrani Z, Beladel A, Kouzou A, Rodriguez J, Abdelrahem M. Four-Wire Three-Level NPC Shunt Active Power Filter Using Model Predictive Control Based on the Grid-Tied PV System for Power Quality Enhancement. Energies 2024; 17(15):3822.

[25] Gony HA, Rashed GI, Badjan A, Bahageel OA, Hualiang H, Shaheen HI. Bat Algorithm-Based Shunt Active Power Filter for Harmonics Control in PV Grid-Connected Systems Under Nonlinear Load. In2024 9th Asia Conference on Power and Electrical Engineering (ACPEE) 2024; 635-639. IEEE.

[26] Hadi HA, Kassem A, Amoud H, Nadweh S. Improve power quality and stability of grid-Connected PV system by using series filter. Heliyon 2024; 10(21).

[27] Soumana RA, Saulo MJ, Muriithi CM. Comparison of MPPT techniques on THD current in a grid-connected photovoltaic system. In2022 4th Global Power, Energy and Communication Conference (GPECOM) 2022; 95-100. IEEE.

[28] Gowtham M, Kaviyarasu N, Dhayanithi R, Praveen C, Hariprabhu M. Maximum Power Tracking and Harmonic Reduction using Optimized P & O MPPT Algorithm. In2022 Second International Conference on Artificial Intelligence and Smart Energy (ICAIS) 2022; 1674-1679. IEEE.

[29] Kiruthiga B, Karthick R, Manju I, Kondreddi K. Optimizing harmonic mitigation for smooth integration of renewable energy: A novel approach using atomic orbital search and feedback artificial tree control. Protection and Control of Modern Power Systems 2024; 9(4):160-76.

[30] Siddeshgowda S, Sidram MH. Mitigation of Voltage and Current Harmonics Using Modified IC Based MPPT Controller and LCL Filter in a GCSPV System. In2022

International Conference on Inventive Computation Technologies (ICICT) 2022; 674-682. IEEE.

[31] Rao TE, Naidu B, Rao JA, Zelie GT, Avinash K, Srisuresh M. Soft Computing Based Hybrid MPPT for Grid Connected Photovoltaic System. In2024 International Conference on Electronics, Computing, Communication and Control Technology (ICECCC) 2024; 1-6. IEEE.

[32] Kurian GM, Jeyanthy PA, Devaraj D. FPGA implementation of FLC-MPPT for harmonics reduction in sustainable photovoltaic system. Sustainable Energy Technologies and Assessments 2022; 52:102192.

[33] Ibrahim NF, Mahmoud MM, Al Thaiban AM, Barnawi AB, Elbarbary ZM, Omar AI, Abdelfattah H. Operation of grid-connected PV system with ANN-based MPPT and an optimized LCL filter using GRG algorithm for enhanced power quality. IEEE Access 2023; 11:106859-76.

[34] Kumar R. Fuzzy particle swarm optimization control algorithm implementation in photovoltaic integrated shunt active power filter for power quality improvement using hardware-in-the-loop. Sustainable Energy Technologies and Assessments 2022; 50:101820.

[35] Navarro MA, Oliva D, Ramos-Michel A, Haro EH. An analysis on the performance of metaheuristic algorithms for the estimation of parameters in solar cell models. Energy Conversion and Management 2023; 276:116523.

[36] Mariprasath T, Basha CH, Khan B, Ali A. A novel on high voltage gain boost converter with cuckoo search optimization based MPPTController for solar PV system. Scientific reports 2024; 14(1):8545.

[37] Poojavarshini S, Kavitha R, Premalatha K, Maithili P. Design and Simulation of DC to DC Boost and SEPIC Converters using MPPT for Photovoltaic system using MATLAB/SIMULINK. In2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA) 2021; 1-5. IEEE.

[38] Satpathy PR, Bhowmik P, Babu TS, Sain C, Sharma R, Alhelou HH. Performance and reliability improvement of partially shaded PV arrays by one-time electrical reconfiguration. IEEE Access 2022; 10:46911-35.

[39] NEZAM AM, MAHMOOD MK, KARIM SM, Addawe A. Evaluation of Incremental Conductance MPPT Algorithm Under Varying Conditions. In2024 21st International Multi-Conference on Systems, Signals & Devices (SSD) 2024; 98-103. IEEE.

[40] Alhusseini H, Niroomand M, Dehkordi BM. A fuzzy–based adaptive p&o mppt algorithm for pv systems with fast tracking and low oscillations under rapidly irradiance change conditions. IEEE Access 2024; 12:84374–84386.

[41] Liu Y, As' arry A, Hassan MK, Hairuddin AA, Mohamad H. Review of the grey wolf optimization algorithm: variants and applications. Neural Computing and Applications 2024; 36(6):2713-35.

[42] Güler N, Irmak E. MPPT based model predictive control of grid connected inverter for PV systems. In2019 8th International Conference on Renewable Energy Research and Applications (ICRERA) 2019; 982-986. IEEE.

[43] Sabri SE, Sujod MZ, Alias WN, Jadin MS. Limiting THD of grid connected photovoltaic system using PWM switching frequency selection based on solar irradiance changing. In2019 IEEE international conference on automatic control and intelligent systems (I2CACIS) 2019; 96-101. IEEE.